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Impact of gain compression factor on modulation characteristics of InGaAs/GaAs self-assembled quantum dot lasers

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Abstract This paper investigates the influence of gain compression factor on the modulation response of InGaAs/GaAs self-assembled quantum dot laser based on rate equations. For different gain compression factors the output power-current characteristics, light emissions of quantum dot laser have been simulated and effect of gain compression factor changes on quantum dot laser is illustrated. Also, small and large-signal response of quantum dot lasers is studied and the impact of the gain compression factor is presented. It explains that increase of gain compression factor, decreases small-signal modulation characteristics, nevertheless, improves large-signal response of quantum dot lasers. It helps to generate better laser signal quality, higher eye and smaller jitter. The large-signal behavior of a laser diode determines its capability for digital data transfer. The modulation speed of quantum dot lasers is of specific importance if such lasers are considered for optical communication systems.

Keywords Gain compression factor · Small signal modulation · Quantum dot lasers

Introduction

Several unique properties of quantum dot lasers make them attractive for many future optical communication applications. Quantum dots (QDs) have been proposed as a possible route to increase the modulation speed of semiconductor lasers. Since its first demonstration, self-assembled quantum

dot lasers attracted great research interest due to their unique physical properties and quantum dot lasers have demonstrated several advantages for use in fiber optic communication systems. A QD laser has the potential to achieve very high differential gain, and the gain spectral width, to be reduced to less than that of planar quantum wells [1]. In contrast, because the planar quantum well has a continuous density of states, the room temperature, probability is small for its electrons and holes to occupy only those states that couple to the lasing mode. In principle, a QD active region can couple every injected electron and hole to the lasing mode so that the change in gain per change in injected electron is increased over a planar well [2]. The advantages of quantum dots over quantum wells are due to their unique density of states resulting from three-dimensional confinement of carriers [3]. Ultralow threshold current and high temperature stability has been demonstrated for 1.3 μm self-assembled quantum dot (QD) lasers by many research groups [4–7]. It is also proved that QD lasers would have a large modulation bandwidth due to the high differential gain of three dimensional confined QD states [8].

The small-signal bandwidth of semiconductor lasers is commonly used to predict their large-signal modulation capabilities. The 1.3 μm emission self-assembled InGaAs/GaAs dots were first formed in 1994 by the alternate supply of Group-III and IV source materials with the quite low growth rate in metal–organic vapor phase epitaxy [9]. Some properties of self assembled quantum dot lasers (SAQDL) have been studied in [9–11]. Simulation of quantum dot lasers with two lasing states for InGaAs/GaAs quantum dot lasers emitting in 1.3 μm wavelength is also presented in [12–14]. Similar studies for (113)B InAs/InP quantum dot lasers are considered in [15, 16] Note that at high bias condition, it has been shown in the aforementioned studies that the transition of lasing state occurs from the ground

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state to the excited state. Differential gain and linewidth enhancement factor are studied in [17, 18]. The influence of the P-doping and tunneling injection on the modulation response of quantum dot lasers are studied in [2, 19]. Impacts of gain compression factor on dynamic and static characteristics quantum dot laser are presented in [20–23].

In the present work, a numerical method based on rate equations is used for modeling the InGaAs/GaAs SAQDL to analyze the light–current and modulation response of the QD-laser is presented. We present a thorough analysis of the modulation characteristics of InGaAs/GaAs SAQDL considering the gain compression factor, carrier relaxation and carrier escape. To our knowledge, this paper is the first one which describes the impact of gain compression factor on modulation response by solving the rate equations. Moreover, in this paper, we study the effect of gain compression factor in both small-signal and large-signal modulation response of InGaAs/GaAs quantum dot lasers which have great importance in optical communication. It is shown that the increase of the gain compression factor causes reduction of modulation bandwidth and improves large-signal properties of quantum dot lasers.

In this paper, first the physics and theory of the InGaAs/GaAs SAQDL is presented and then results are discussed. The role of gain compression factor is highlighted and it is shown that it plays an important role in the quantum dot laser modulation. Finally, conclusions are presented in the last section.

Physics and modeling

In the following, a numerical model is used to study carrier dynamics in the lowest energy level of an InGaAs/GaAs quantum dot system. In this model, dominant dynamics of carriers and photons such as carrier relaxation, capture and re-excitation rates to dots, radiative and nonradiative recombination rates of carriers, inhomogeneous broadening of dot resonant energy primarily due to the size fluctuation of dots are considered. The most popular and useful way to deal with the carrier and photon dynamics in lasers is to solve the rate equations for carriers and photons. Here, we present a coupled set of rate equations to calculate the lasing properties of quantum dot lasers. Our model describing the carrier dynamics in QD lasers is based on the experimental works [10, 24, 25]. It is assumed that only a single, discrete electron–hole ground state is formed inside a quantum dot and that charge neutrality always holds on each dot. Figure 1 shows the physical structure and scheme of the carrier transition process in the active region of self-assembled quantum dot lasers. In this figure, N_s and N_q are carrier numbers in separate confinement heterostructure (SCH) and wetting layer, respectively. We also consider that N_n is the carrier number in the quantum dot. The

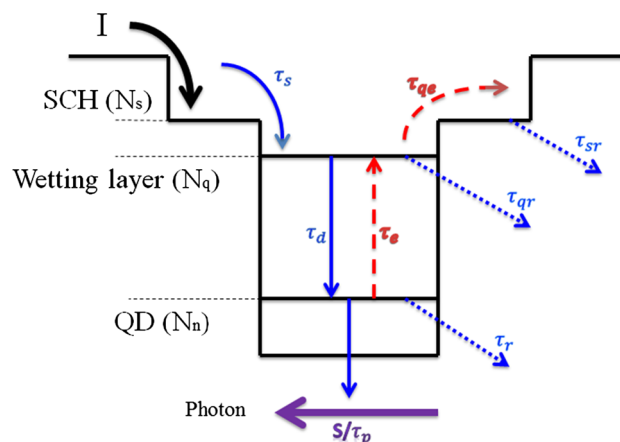


Fig. 1 Energy band diagram for the active region of InGaAs/GaAs SAQDL

injected carriers diffuse through the SCH layer, relax into the quantum well (QW), and then relax into the dot.

Above lasing threshold current, carriers in the ground state emit photons into the lasing mode primarily due to the stimulated emission process. To study the gain compression factor impact on quantum dot laser, for simplicity in this model, we neglect cavity internal modes and we consider a single mode rate equation model. The rate equations for the carrier–photon system are:

$$\frac{dN_s}{dt} = \frac{I}{e} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_{sr}} + \frac{N_q}{\tau_{qe}}, \quad (1)$$

$$\frac{dN_q}{dt} = \frac{N_s}{\tau_s} + \frac{N_n}{\tau_e} - \frac{N_q}{\tau_{qr}} - \frac{N_q}{\tau_{qe}} - \frac{N_q}{\tau_d}, \quad (2)$$

$$\frac{dN_n}{dt} = \frac{N_q}{\tau_d} - \frac{N_n}{\tau_r} - \frac{N_n}{\tau_e} - \frac{(c/n_r)g_{tot}\Gamma}{1 + \varepsilon_m \Gamma S/V_a} S, \quad (3)$$

$$\frac{dS_m}{dt} = \frac{(c/n_r)g_{tot}\Gamma}{1 + \varepsilon_m \Gamma S/V_a} S - \frac{S}{\tau_p} + \frac{\beta N_n}{\tau_r}. \quad (4)$$

Here, V_a is the active region volume β is the spontaneous-emission coupling coefficient and I is the injected current. The associated time constants are: diffusion time in the SCH region (τ_s), carrier non-radiative recombination lifetime in the SCH region (τ_{sr}), carrier re-excitation time from the quantum dot to the wetting layer (τ_e), carrier non-radiative recombination lifetime in the wetting layer (τ_{qr}), carrier relaxation lifetime into quantum dot (τ_d) and non-radiative recombination lifetime in the quantum dot (τ_r). For simplicity, carrier re-excitation lifetime from the quantum well to the SCH region (τ_{qe}) is neglected. The maximum optical gain at the center of the broadening function is given as [20]:

$$g_m^{(1)} = \frac{2\pi e^2 \hbar N_D}{cn_r \varepsilon_0 m_0^2} \frac{|P_{cv}^\sigma|^2}{E_{cv} \Gamma_{in\ hom}} (2P - 1), \quad (5)$$



where $\varepsilon_0 = \Gamma_{\text{inhom}}/2.35$ and the full-width at half maximum (FWHM) is Γ_{inhom} , $|P_{\text{cv}}^\sigma|^2$ is the transition matrix element, n_r is the refractive index, E_{cv} is the inter-band transition energy. According to Pauli's exclusion principle, occupation probability in the quantum dot ground state P is related to N as [22]:

$$P = N/(2N_D V_a), \quad (6)$$

where N is the population of carriers in the dot and N_D is the dot density.

The maximum optical gain, including nonlinear susceptibility, is written as [26]:

$$g_{\text{tot}} = g_m^{(1)} + g_m^{(3)} = g_m^{(1)} [1 - \varepsilon_m \Gamma S / V_a] \cong \frac{g_m^{(1)}}{1 + \varepsilon_m \Gamma S / V_a}, \quad (7)$$

where ε_m is the third-order nonlinear coefficient [27].

$$\varepsilon_m = \frac{\hbar q^2}{2\pi n_r^2 m_0^2 \varepsilon_0} \frac{|P_{\text{cv}}^2|}{\hbar \omega} \frac{\tau_p}{F_{\text{ho}}}, \quad (8)$$

Coverage factor is considered as:

$$\xi = N_D V_D, \quad (9)$$

where V_D is the volume of a dot. The photon lifetime in the cavity τ_p is given as:

$$\tau_p^{-1} = (c/n_r) [\alpha_i + \ln(1/R_1 R_2) / (2L_{\text{ca}})], \quad (10)$$

where R_1 and R_2 are the cavity mirror reflectivity coefficients and α_i is the internal loss.

To calculate the small-signal modulation response of the laser we have applied the current $I = I_0 + I(\omega_m) \exp(i\omega_m t)$ with a modulation angular frequency of ω_m , to the laser. By use of calculation of [21], the resultant modulation response function of the laser is given as:

$$M(\omega_m) = \frac{1}{(1 + \omega_m^2 \tau_d^2)^{1/2} (1 + \omega_m^2 \tau_s^2)^{1/2}} \frac{Q}{[(\omega_m^2 - \omega_r^2)^2 + \gamma^2 \omega_m^2]^{1/2}}, \quad (11)$$

$$\omega_r^2 = \frac{\Gamma S_0 g'}{\tau_p (1 + \varepsilon_m \Gamma S_0 / V_a)} \left[1 + \frac{\varepsilon_m / V_a}{g' \tau_r} \right], \quad (12)$$

$$\gamma = \frac{\Gamma S_0 g'}{1 + \varepsilon_m \Gamma S_0 / V_a} + \frac{\varepsilon_m \Gamma S_0 / V_a}{\tau_p (1 + \varepsilon_m \Gamma S_0 / V_a)} + \frac{1}{\tau_r}, \quad (13)$$

$$Q = \frac{\Gamma S_0 g'}{1 + \varepsilon_m \Gamma S_0 / V_a}, \quad (14)$$

and g' is differential gain:

$$g' = \frac{c}{n_r} \frac{\partial g_m^{(1)}}{\partial N}, \quad (15)$$

where ω_r is the relaxation oscillation frequency and γ is damping factor. The 3-dB bandwidth limited by the relaxation lifetime of τ_d is given as:

$$f_{\text{3dB}} = (2\pi\tau_d)^{-1}, \quad (16)$$

We have considered typical SAQDL material and geometrical parameters such as those given in Table 1 [8, 24, 28].

Table 1 Parameters used in SAQDL modeling [8, 24, 28]

Symbol	Description	Value
τ_0	Carrier relaxation lifetime	10 ps
τ_s	Carrier capture time in SCH region	1 ps
τ_{sr}	Spontaneous emission lifetime in SCH	2.8 ns
τ_{qr}	Carrier recombination lifetime in QW	3 ns
τ_r	Recombination lifetime in QD	2.8 ns
τ_{qe}	Carrier scape time from QD to WL	3 ns
R	Radius of a QD (Cylindrical shape)	8 nm
H	Height of a QD (Cylindrical shape)	5 nm
R_1	Right facet reflectivity	30 %
R_2	Left facet reflectivity	90 %
L_{ca}	Cavity length	900 μm
Γ	Optical confinement factor	6 %
α_i	Intrinsic absorption coefficient	6 cm^{-1}
n_r	Refractive index	3.5
β	Spontaneous emission coupling coefficient	10 ⁻⁴
Δ	Spin-orbit interaction energy of QD material	0.35 eV
E_g	Band gap energy	0.8 eV
V_a	Active region volume	2.2 $\times 10^{-16} \text{ m}^3$



Results and discussions

By using the rate Eqs. (1)–(4) and Eq. (11), it is possible to study the dynamic characteristics and modulation response of InGaAs/GaAs quantum dot lasers. Results of simulations are presented in this section. Value of gain compression factor is chosen around $\varepsilon_m = 10^{-22} \text{ m}^3$, which it corresponds to the regular formalism [29, 30].

In Fig. 2 photon density versus time for different gain comparison factors has been illustrated. As it can be seen, by increasing the gain compression factor, the carrier relaxation oscillation frequency and photon number has been reduced. It is related to the decrease of the optical gain of the quantum dot laser.

In Fig. 3 output power versus injected current for different gain compression factors have been presented. As we can see from Fig. 3, increase in the gain compression factor leads to decrease in output power and slope efficiency. It is due to the fact that when gain compression factor raises the nonlinear saturation gain reduces and it leads to decrease of differential gain that, it contributes to degrade in the output power and slope efficiency. Increase of gain compression factor does not affect the threshold current of quantum dot laser. It is because gain compression factor changes gain of the laser in the injection currents of the upper threshold current.

Gain compression factor, causes output power rollover in quantum dot lasers. In Fig. 3, increase of gain compression factor, reduces threshold of the output power rollover to lower injection currents and it starts in lower injection currents. For gain compression factor of 10×10^{-22} and 20×10^{-22} output power rollover appears at injection currents of around 7 and 3 mA respectively. Figure 4 shows the modulation response for different injected currents. It illustrates that, increase of injected

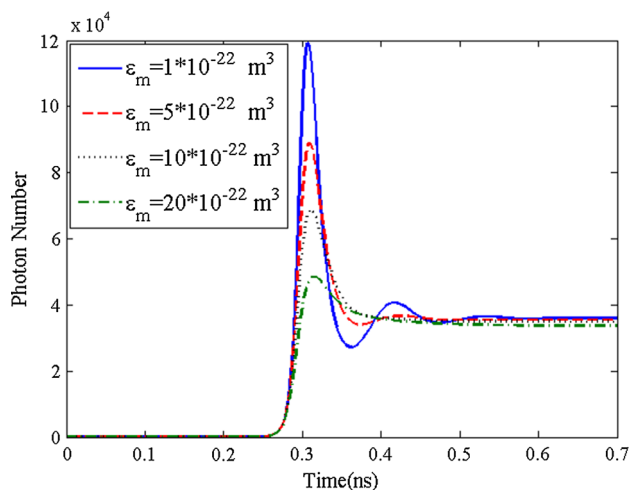


Fig. 2 Photon density versus time for various gain compression factors

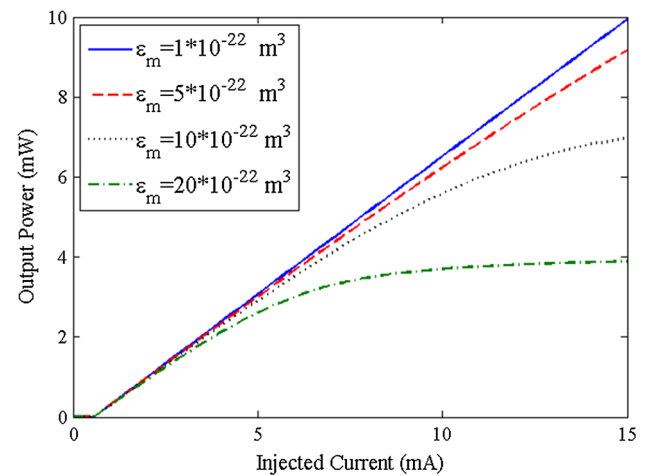


Fig. 3 Light current characteristics of quantum dot lasers for various values of gain compression factors

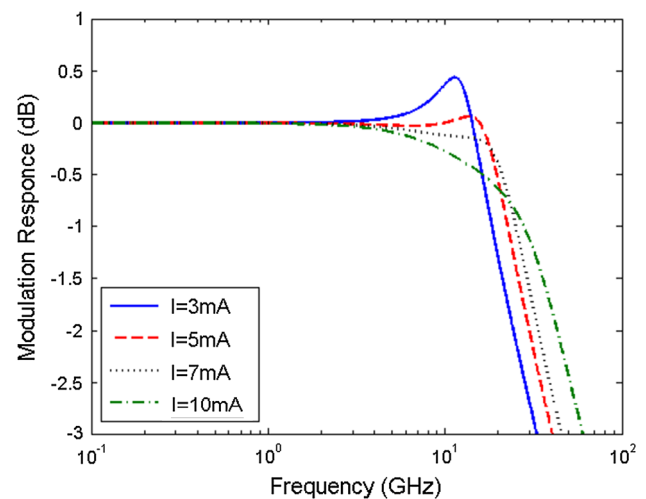


Fig. 4 Modulation response of quantum dot laser for different injected currents

current leads to increase modulation bandwidth and decrease relaxation oscillation frequency and peak amplitude of quantum dot laser. This corresponds to results of InAs/InP quantum dot lasers [31].

Quantum dot lasers suffer from larger gain compression factors (10^{-22} – 10^{-21} m^3) as compared to their quantum well counterparts (10^{-25} – 10^{-23} m^3) which can also alter the modulation dynamics [32]. Figure 5 illustrates modulation response for different gain compression factors. This figure indicates that relaxation oscillation frequency, peak amplitude, and modulation bandwidth reduce with increasing of the gain compression factor. The larger gain compression clearly suppresses the resonance peak and reduces the modulation bandwidth. The resonance frequency for 1×10^{-22} is 11.4 GHz and by increase of gain compression factor, it is decreased.



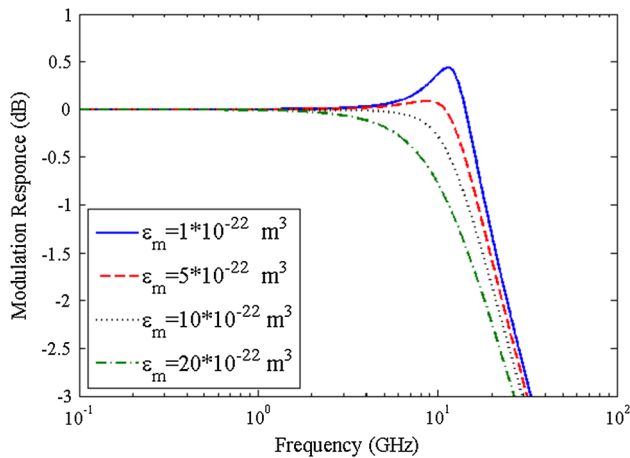


Fig. 5 Modulation response of quantum dot laser for different gain compression factors

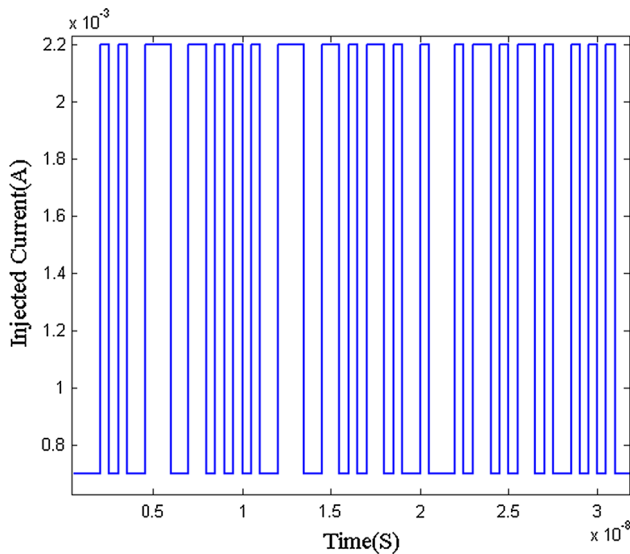


Fig. 6 Digital injected current versus time

To study large-signal properties of quantum dot lasers, we introduce a digital injected current to the laser. In Fig. 6, the injected current changes between 0.0007 and 0.0022 A every 0.5 ns. Figure 7 shows the digital photon number for the repetition frequency of 2 Gib/s in $1 \times 10^{-22} \text{ m}^3$ gain compression factor.

In Fig. 7, it is demonstrated, when injected current increased to higher values of more than threshold current, after a small turn on delay, the photon number is increased to higher values.

By using digital injected current, it is possible to accurately model the measured eye diagram [33]. Figure 8a–c show eye diagram for gain compression factor with values

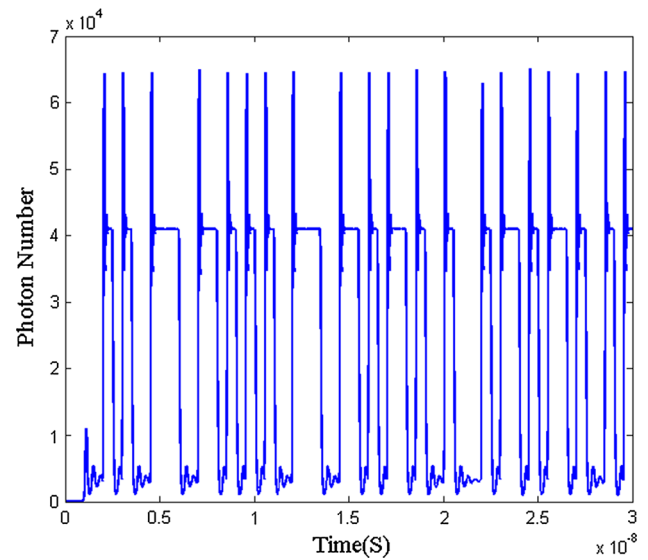


Fig. 7 Large-signal photon number of QD laser in $1 \times 10^{-22} \text{ m}^3$ gain compression factor

of 1×10^{-22} , 5×10^{-22} , and $10 \times 10^{-22} \text{ m}^3$. It is shown that, for low gain compression factors the eye height is low. Increase of gain compression factor, appears the larger eye height and smaller jitter. The eye diagram is improved by increasing of gain compression factor. It is notable that the eye height is directly associated with the noise. By increasing gain compression factor, eye height increases and so eye becomes more open and noise decreases.

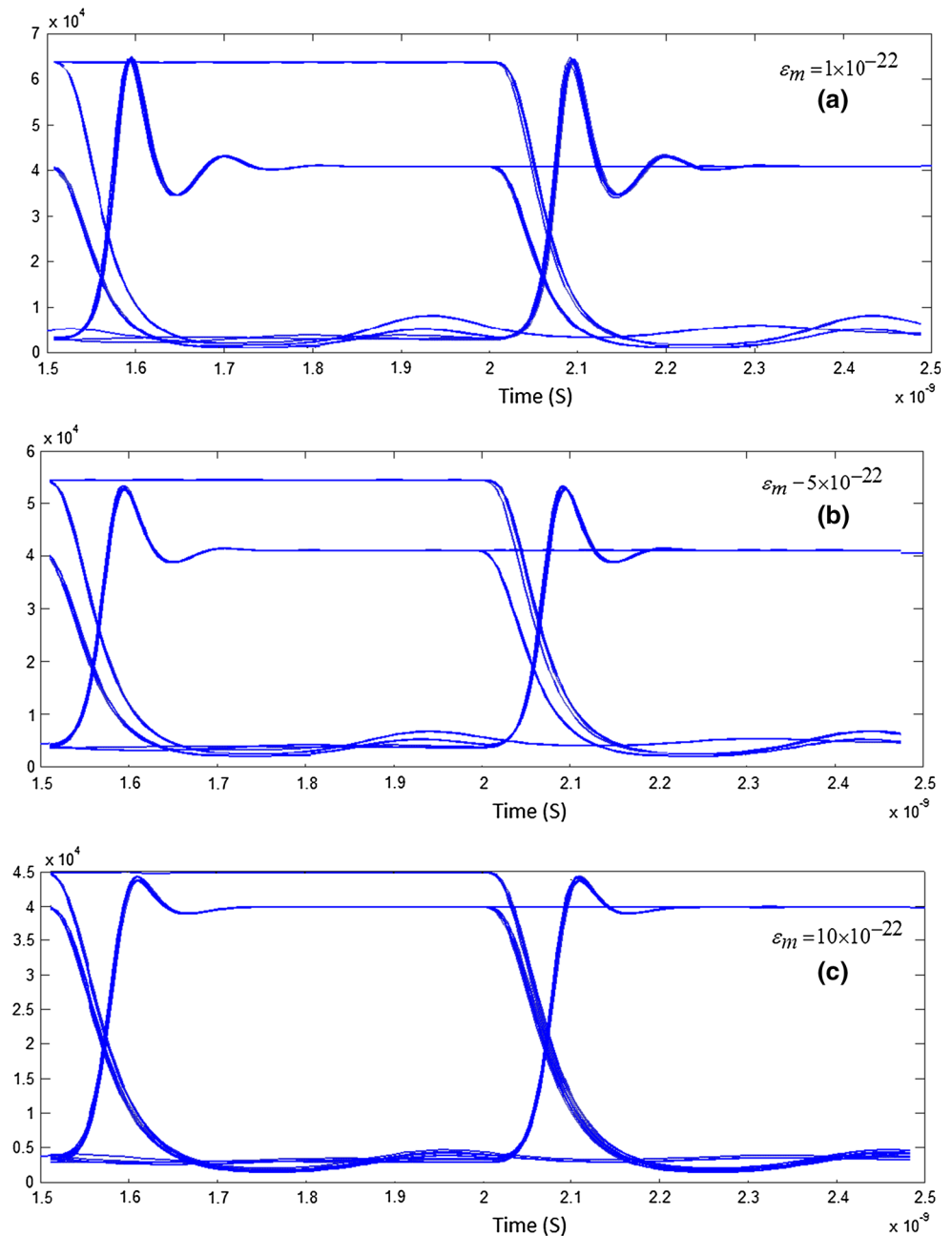
It is demonstrated that, quantum dot lasers with a large nonlinear gain compression factor have narrow small-signal bandwidth, but are capable of large-signal modulation at very high rates.

Conclusions

In this paper a theoretical model has been used to investigate the modulation properties of InGaAs/GaAs quantum dot laser. The numerical model takes into account gain compression factor. Variation of gain compression factor, does not affect ground state threshold current of the laser but it degrades the photon number and consequently, reduction of output power in the InGaAs/GaAs quantum dot laser is demonstrated. It is shown that increase of the gain compression factor, decrease resonance frequency, relaxation oscillation frequency and modulation bandwidth. Despite gain compression factor limits small-signal response of the quantum dot lasers, the eye diagram of the large-signal modulation of the laser is improved for large values of gain compression factor. As we increase gain



Fig. 8 Eye diagram of quantum dot laser diagram for the repetition frequency of 2 Gib/s in different gain compression factors



compression factor, we realize clear eye opening with small jitter. QD lasers with a high nonlinear gain compression factor have narrow small signal bandwidth, but are capable of large-signal modulation at very high rates.

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